GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 14, PAGES 2069-2072, JULY 15, 1999

The Barrier Layer in the Western Tropical Atlantic Ocean

K. Pailler

Laboratoire de Physique des Océans, Université de Bretagne Occidentale, Brest, France

B. Bourlès and Y. Gouriou

Centre IRD de Bretagne, Plouzané, France

Abstract. In the tropical oceans, where the temperature is roughly homogenous in the upper layer, vertical variations of salinity may be responsible for significant density stratifications. In this study on the western Tropical Atlantic Ocean, it is shown that fresh surface waters of the Amazon River discharge may induce a strong halocline in the 3-30 m depth range. This halocline induces a pycnocline that acts as a barrier for mixing between the surface and the subsurface waters. The fresh surface waters are generally associated with positive anomalies of the sea surface temperature. These positive anomalies cover a large part of the basin in boreal summer-fall, following the maximum Amazon River discharge, which may have a significant importance for the ocean-atmosphere exchanges.

1. Introduction

The climate variability of the Tropical Atlantic Ocean, and of the surrounding American and African countries, is strongly dependent on the location of the Intertropical Trade winds Convergence Zone (hereafter ITCZ), which is related to the sea surface temperature (hereafter SST) pattern. At seasonal to decadal timescales, tropical and interhemispheric SST anomalies and the position and intensity of the ITCZ are strongly related to the rainfall over the Nordeste and the Sahel [e.g., *Ward and Folland*, 1991; *Servain*, 1991]. From a statistical point of view, the western Tropical Atlantic is not an area of high amplitude of the two main modes of SST interannual to interdecadal variability, *i.e.* the interhemispheric dipole and equatorial modes [*Zebiak*, 1993; *Enfield and Mayer*, 1997]. However, the majority of the SST and heat anomalies observed in the eastern equatorial Atlantic are first found in the western Atlantic, and are primarily related to wind anomalies occurring in the western equatorial basin [*Carton et al.*, 1996; *Servain et al.*, 1998]. In this region, the swift North Brazil Current (hereafter NBC) carries southern warm upper ocean waters toward the Northern Hemisphere [*Metcalf*, 1968]. After crossing the equator, the NBC exhibits a very complex behavior, and feeds surface and subsurface eastward flows at different depths and different latitude [e.g., *Schott et al.*, 1998; *Bourlès et al.*, 1999a,b]. These eastward currents issued from the western boundary are of major importance for the linkage between the tropical and subtropical circulation [e.g., *Mayer and Weisberg*, 1993].

An other particular interest of the western Tropical Atlantic Ocean lies in the presence of the Amazon river discharge, which is the most important of the world [*Baumgartner and Reichel*, 1975]. This runoff is responsible for most of the fresh surface waters observed in the western tropical Atlantic, and largely contributes to the freshwater budget of the equatorial Atlantic [*Yoo and Carton*, 1990; *Dessier and Donguy*, 1994; *Lentz*, 1995]. Recent studies have pointed out to the role of the salinity vertical distribution on the upper ocean stratification, and consequently on the mixed layer depth and vertical heat exchanges [e.g., *Lukas and Lindstrom*, 1991; *Sprintall and Tomczak*, 1992 –hereafter ST92-; *Vialard and Delecluse*, 1998]. Over most of the World Ocean, variations of mixed layer depth are primarily controlled by temperature; however, fresh surface waters or a subsurface salinity maximum present in the tropics may induce a marked halocline (high vertical gradient of salt), inducing a pycnocline that prevents any cooling of the mixed layer by underlying waters. *Lukas and Lindstrom* [1991] defined the distance between the bottom of the mixed layer, associated with the halocline, and the top of the thermocline as the 'barrier layer' (hereafter BL). ST92 indicate that the BL is a climatological characteristic of the three tropical oceans. In the western tropical Atlantic Ocean, ST92 explain the presence of a BL to be mainly due to high salinity waters formed in the central subtropical gyres of both hemispheres, and advected in the region within the North and South Equatorial Currents. However, their analysis is based on a climatology [*Levitus*, 1982], issued from a spatial and temporal objective analysis that is susceptible to artificially generate a BL. Furthermore, the vertical resolution of the climatological data set is relatively poor, which may therefore mask some salinity and/or temperature vertical variations. Thus, we may also expect the Amazon runoff to contribute to the formation of a BL in this particular region.

The purpose of this study is to analyze, from *in situ* and high vertical resolution conductivity-temperature-depth (CTD) profiles, the surface layers in the western equatorial Atlantic, in order to describe the BL in this region. The paper is organized as follows. Data are briefly described in Section 2. Results that show up the BL and its characteristics are presented in Section 3. A concluding discussion is proposed in Section 4.

2. Data Presentation

The data set used for this study consists of 2673 CTD profiles selected in the western tropical Atlantic, bounded by the latitudes 10°S and 15°N, west of the 30°W meridian (Figure 1). Most of them are issued from the National Oceanographic Data Center (World Ocean Database 1998), and were selected insofar as the profiles presented high vertical resolution (better than 8 m, and better than 5 m for

Paper number 1999GL900492.
0094-8276/99/1999GL900492$05.00

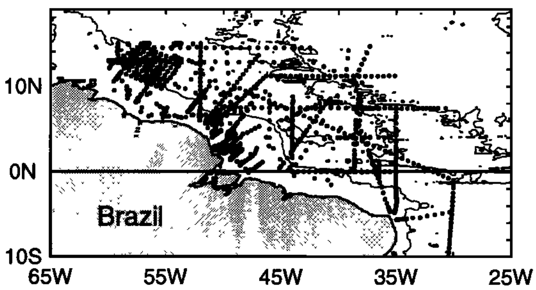

Figure 1. Map of the western equatorial Atlantic, along with the distribution of the CTD profiles (dots) used in this study. Isobath 4000 m depth is also represented.

about 95% of the profiles) in the upper layers. We included 350 high vertical resolution (1 m or 2 m according to the cruise) CTD profiles obtained during four recent cruises, carried out in the framework of the French WOCE (World Ocean Circulation Experiment) programs CITHER (Circulation Thermohaline, 1993-1994) and ETAMBOT (Etude du Transport Atlantique Méridien dans le Bassin Ouest Equatorial, 1995-1996). These four cruise data sets are presented in *Arhan et al.* [1998] and *Bourlès et al.* [1999*b*].

3. Results

Figure 2 shows a typical salinity distribution along a section perpendicular to the Brazil coast off the Amazon mouth. This section was carried out between 0°N-45°W and 8°20'N-41°W in May 1996 during the ETAMBOT 2 cruise. From 0°N to 3°30'N, very low salinity values (down to 32.2 at 2°N) are observed at the surface, within a 20 m depth layer. This surface fresh water is associated with high silicate concentrations (up to 9 μmol kg^{-1}; Figure 3), which proves its continental origin through the Amazon discharge [*Ryther et al.*, 1967]. It is also associated with a high temperature, higher than 28.5°C and up to 29°C where sea surface salinity (SSS) is minimum, whereas SST is at least one degree Celsius lower where SSS is about 36 (Figure 3). At depth, from 0°N to 3°N, salinity maximum water is present, with values up to 36.8 near 100 m depth, and higher than 36.6 from 60 m to 120 m depth (Figure 2). This water, formed in the Southern Hemisphere subtropical gyre, is entrained into the region within the North Brazil Undercurrent that flows northwestward along the Brazil continental shelf slope [*Stramma et al.*, 1995]. Individual temperature, salinity, and

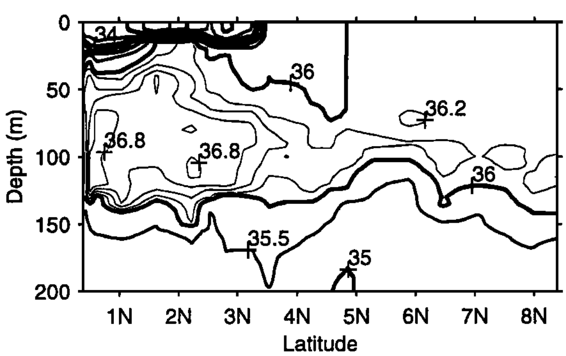

Figure 2. Vertical salinity section, between 0°N-45°W and 8°20'N-41°W, obtained in May 1996 during the ETAMBOT 2 cruise.

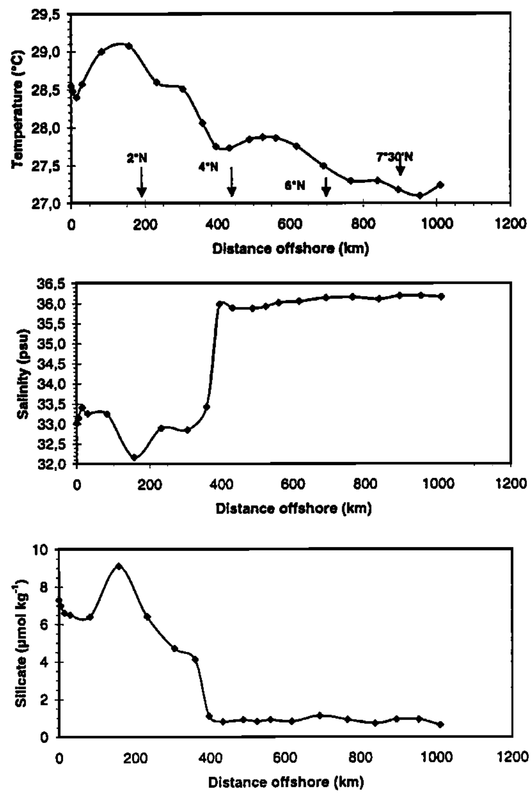

Figure 3. Surface temperature, salinity, and silicate (up to bottom) concentrations observed in May 1996 between 0°N-45°W and 8°20'N-41°W.

density profiles, carried out along this section at 2°22'N-44°13'W, *i.e.* around the center of the Amazon water plume, clearly show that the haloclines are associated with well marked pycnoclines (Figure 4). While temperature, of about 28°C, is nearly homogeneous from the surface down to 60 m depth, salinity increases from 33 to 36.3 from the surface to 15 m depth. This salinity increase induces a shallow pycnocline centered near a depth of 10 m, where the density varies from 21 kg.m^{-3} to 23.5 kg.m^{-3} in a few meters. Below 60 m, the density increases regularly with depth down to 150 m, where a pycnocline is associated with the bottom of the salinity maximum layer and the main thermocline. These profiles illustrate the presence of a BL, here observed from 15 m depth down to about 60 m depth, base of the isothermal layer, isolating the shallow mixed layer from cooler and deeper waters. Such vertical distributions, observed for many CTD profiles, clearly indicate that in the western equatorial Atlantic Ocean salinity may prevail in determining the mixed layer depth, which can be very shallow.

The difference, ΔZ, between the depths of the maximum vertical gradients of temperature (main thermocline) and density (main pycnocline) has been used to define the BL thickness. Following ST92, we built up seasonal *-i.e.* February, March, April (FMA); May, June, July (MJJ); August, September, October (ASO), and November, December, January (NDJ)- handmade charts of the spatial distribution of the BL. The value ΔZ = 40 m has been arbitrarily chosen as the minimum significant value for the BL thickness defined through our criteria. The vertical distributions of salinity, temperature and density have been examined to determine which mechanism is responsible for

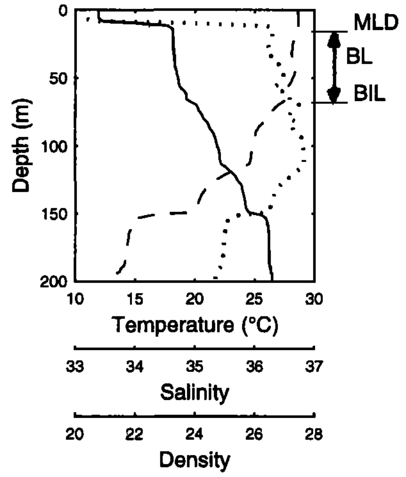

Figure 4. Vertical salinity (dotted line), temperature (dashed line), and density (full line) profiles, obtained at 2°22'N-44°13'W in May 1996 during the ETAMBOT-2 cruise. The Mixed Layer Depth (MLD), Base of the Isothermal Layer (BIL) and Barrier Layer (BL) vertical extension are also indicated.

the BL formation when present, that is to say either surface fresh water or subsurface salinity maximum water, or both.

The FMA, MJJ and NDJ charts (not shown) are in rather good agreement with those obtained by ST92 (their Figure 3). They confirm the role of the subsurface salinity maximum for the formation of the BL, mainly along the Brazil coast and in the north of the studied area. These charts also show regions of BL due to fresh surface waters that follow the coast over about 300 km width around and north of the Amazon and Orinoco mouths, as illustrated in Figures 2 and 3 for a May cruise, and dominantly of fluvial origin [*Dessier and Donguy*, 1994; *Lentz*, 1995]. We focus here on the season ASO that exhibits striking differences with the results of ST92. Though we also find in this season an influence of subsurface salinity maximum, the principal mechanism that induces a BL is the presence of low salinity surface water, yet expected to be a process of minor importance by these authors. Figure 5 shows the ASO chart, along with the position of the ITCZ: the shaded areas correspond to regions where low salinity surface waters induce a BL. Note that the BL zones have been drawn only where data are available, whatever the year, and no major interpolation, or extrapolation, has been made. Thus, the BL zones may extend on larger areas than indicated. This BL is present in a large area extending from 60°W to 35°W. The zonal band spreading eastward perfectly coincides with the fresh tongue observed in September from the climatology, that indicates SSS lower than 35.5 across the whole basin around the 5°N-8°N latitudinal band [*Dessier and Donguy*, 1994]. Although the ITCZ lies above this fresh tongue, many studies [e.g., *Ryther et al.*, 1967; *Kidd and Sanders*, 1979; *Ternon et al.*, 1999] and available silicate measurements show up that the fresh surface waters are generally associated with high silicate concentrations, and have therefore also a river origin. *Lefèvre et al.* [1998] clearly show, from Coastal Zone Color Scanner (CZCS) climatology and *in situ* measurements, that the Amazon outflow is mainly responsible for the low surface salinities observed as far as 25°W in September-October. At this time of the year, the Amazonian water partly flows eastward within the North Equatorial Countercurrent, fed by the NBC retroflection, and partly continue northwestward towards the Caribbean Sea, as was well illustrated from CZCS imagery [*Müller-Karger et al.*, 1988]. Furthermore, the Orinoco, fourth river in the world in term of run-off, has its maximum discharge in August-September [*Baumgartner and Reichel*, 1975]. Thus, river outflows play a role of prime importance in the formation of a BL that extends eastward and northwestward in boreal summer-fall, a few months after the Amazon and during the Orinoco Rivers maximum discharges.

We mentioned that the SST reaches 29.5°C within the fresh surface water plume observed in May 1996 off the Amazon mouth, while it is lower than 28°C when salinity is about 36 (Figure 3). The available CTD data, obtained during different years and seasons, do not allow us to objectively build seasonal charts of SSS and SST, in order to point out the eventual impact of low SSS on SST. However, the T-S diagram (Figure 6) built from all the CTD measurements available at 2 m depth clearly shows that the SST higher than 28°C are generally associated with SSS lower than 35 (points with salinity lower than 35 and temperature below 27°C were measured north of 10°N in boreal winter). Many studies have shown the close correlation that exists between the SST variations and the location of the ITCZ. Thus, we cannot dismiss the possibility that the high SST associated to low SSS could also be a consequence of a relative minimum of latent heat loss (less evaporation). The data at hand cannot allow to separate the two processes. However, the positive SST anomalies associated with surface fresh waters observed during ASO south (notably off the Amazon mouth) and north of the mean ITCZ location (Figure 5) cannot be attributed to the presence of the ITCZ. Wind, SST and SSS measurements obtained in 1998 from a mooring of the Pilot Research

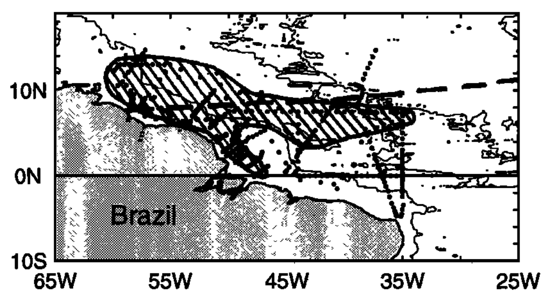

Figure 5. Mapping of the BL for August-September-October. Shaded area corresponds to the basin region where surface fresh waters induce a BL (for details, see text).

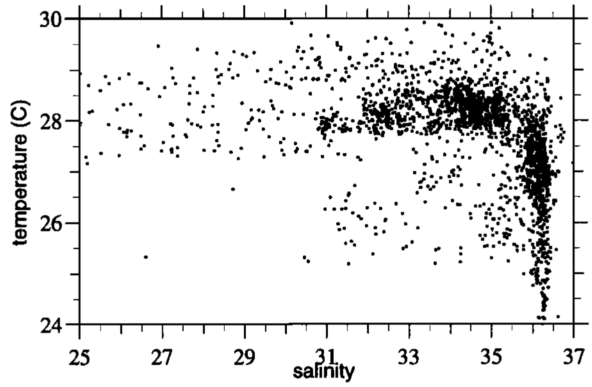

Figure 6. Temperature-Salinity diagram obtained at 2 m depth from 2635 CTD profiles carried out in the 10°S-15°N latitude and 60°W-30°W longitude ranges.

Moored Array in the Tropical Atlantic (PIRATA; *Servain et al.*, 1998) located at 8°N-38°W support the linkage between SST increase and the presence of fresh surface waters inducing a BL. There, a strong decrease of the SSS (from 36.4 down to 35) was observed as early as mid-May 1998 associated with an increase of the temperature above 28°C over a 40 m depth surface layer, while the wind data indicate the presence of the ITCZ from the end of June only (not shown; please refer to http://www.ifremer.fr/ird/pirata/miroir).

6. Conclusions

This analysis based on high vertical resolution CTD data confirms earlier studies that pointed out the dominant role of salinity in determining the mixed layer depth in the tropics. We show for the western Equatorial Atlantic Ocean that the fresh surface waters originating from rivers discharge, and mostly from the Amazon River, play an important role for the formation of a BL. In agreement with the seasonal cycle of the Amazon discharge and the circulation, the BL extends over a large part of the equatorial basin north of the equator in boreal summer-fall.

In the Pacific Ocean, the possible implication of high SST associated with the BL in the El Niño / Southern Oscillation phenomenon has been evoked [*Lukas and Lindstrom*, 1991; *Ando and McPhaden*, 1997]. In the Atlantic Ocean, the BL is likely to influence the climate as well. According to *Hastenrath* [1990], the ITCZ is shifted farther north than usual at the end of the boreal winter during La Niña years. This induces an increase of the precipitation above the Amazon basin, thus an increase of the Amazon discharge. An eventual larger northward spreading of the positive SST anomalies induced by higher runoff could then contribute to maintain the atmospheric convection north of its usual location, and consequently contribute to a northward shift of the ITCZ during the following boreal summer-fall months. Much work has been done on the processes that could potentially give rise to SST variations, indicating that they are the result of very complex interaction between variations of surface flux and oceanic processes [e.g., *Hayes et al.*, 1991]. However these studies did not consider the impact of the river runoffs. In conclusion, we would like to point out that it is necessary to take into account runoffs in any numerical experiments carried out for climatic studies in the Atlantic Ocean. While no sufficiently long records of simultaneous oceanic and atmospheric parameters exist, such numerical experiments would help to investigate the real impact of fresh Amazon water lenses on the mixed layer depth and on the ocean-atmosphere exchanges, and thus their potential role on the climate.

Acknowledgments. We greatly acknowledge Gilles Reverdin, Claude Oudot and Alain Dessier for very helpful discussions and comments. We would also thank the scientific team of PIRATA for giving free access to the community the quasi-real time PIRATA data sets via internet.

References

Ando, K., and M. J. McPhaden, Variability of surface layer hydrography in the tropical Pacific Ocean, *J. Geophys. Res.,102, C10*, 23,063-23,078, 1997.

Arhan, M., H. Mercier, B. Bourlès, and Y. Gouriou, Hydrographic sections across the Atlantic at 7°30'N and 4°30'S, *Deep-Sea Res., I, 45*, 829-872, 1998.

Baumgartner, A., and E. Reichel, The world water balance: Mean annual global, continental and maritime precipitation, evaporation and run-off, *Elsevier*, New-York,179pp., 1975.

Bourlès, B., R. L. Molinari, E. Johns, W. D. Wilson, and K. Leaman, Upper layer currents in the western Tropical North Atlantic, *J. Geophys. Res., 104, C1*, 1361-1375, 1999a.

Bourlès, B., Y. Gouriou, and R. Chuchla, On the circulation in the upper layer of the western equatorial Atlantic, *in press, J. Geophys. Res.*, 1999b.

Carton, J. A., X. Cao, B. S. Giese, and A. M. da Silva, Decadal and interannual SST variability in the Tropical Atlantic Ocean, *J. Phys. Oceanogr., 26*, 1165-1174, 1996.

Dessier, A., and J. R. Donguy, The sea surface salinity in the Tropical Atlantic between 10°S and 30°N; seasonal and interannual variations (1977-1989), *Deep-Sea Res., I, 41*, 81-100, 1994.

Enfield, D. B., and D. A. Mayer, Tropical Atlantic SST variability and its relation to El Niño-Southern Oscillation, *J. Geophys. Res., 102*, 929-945, 1997.

Hastenrath, S., Diagnostics and Prediction of Anomalous River Discharge in Northern South America, *J. of Climate, 3, 10*, 1080-1096, 1990.

Hayes, S. P., P. Chang, and M. J. McPhaden, Variability of the sea surface temperature in the eastern equatorial Pacific Ocean during 1986-1988, *J. Geophys. Res., 96*, 10,553-10,566, 1991.

Kidd, R., and F. Sander, Influence of Amazon River discharge on the marine production system off Barbados, West Indies, *J. Mar. Res., 37, 4*, 669-681, 1979.

Lefèvre, N., G. Moore, J. Aiken, A. Watson, D. Cooper, and R. Ling, Variability of pCO_2 in the tropical Atlantic in 1995, *J. Geophys. Res., 103, C3*, 5623-5634, 1998.

Lentz, S., Seasonal variations in the horizontal structure of the Amazon plume inferred from historical hydrographic data, *J. Geophys. Res., 100, C2*, 2391-2400, 1995.

Levitus, S., Climatological atlas of the world ocean, *Rep. NOAA Prof. Paper 13*, 173pp., NOAA, Rockville, Md., 1982.

Lukas, R., and E. Lindstrom, The Mixed Layer of the Western Equatorial Pacific Ocean, *J. Geophys. Res., 96*, 3343-3357, 1991.

Mayer, D. A., and R. H. Weisberg, A description of COADS surface meteorological fields and the implied Sverdrup transports for the Atlantic Ocean from 30°S to 60°N, *J. Phys. Oceanogr., 23*, 2201-2221, 1993.

Metcalf, W., Shallow currents along the northeastern coast of South America, *J. Mar. Res., 26*, 232-243, 1968.

Müller-Karger, F. E., C. R. McClain, and P. Richardson, The dispersal of Amazon's water, *Nature*, 333, 56-59, 1988.

Ryther, J. H., D. W. Menzel, and N. Corwin, Influence of the Amazon River outflow on the ecology of the Western Tropical Atlantic, I. Hydrography and nutrient chemistry, *J. Mar. Res., 25, 1*, 69-83, 1967.

Schott, F. A., J. Fischer, and L. Stramma, Transports and pathways of the upper-layer circulation in the western tropical Atlantic, *J. Phys. Oceanogr., 28*, 1904-1928, 1998.

Servain, J., Simple climatic indices for the tropical Atlantic Ocean and some applications, *J. Geophys. Res., 96*, 15,137-15,146, 1991.

Servain, J., A. J. Busalacchi, M. J. McPhaden, A. D. Moura, G. Reverdin, M. Vianna, and S. E. Zebiak, A Pilot Research Moored Array in the Tropical Atlantic (PIRATA), *Bull. Amer. Meteor. Soc., 79, 10*, 2019-2031, 1998.

Sprintall, J., and M. Tomczak, Evidence of the barrier layer in the surface layer of the tropics, *J. Geophys. Res., 97*, 7305-7316, 1992.

Stramma, L., J. Fischer, and J. Reppin, The North Brazil Undercurrent, *Deep-Sea Res., I, 42*, 773-795, 1995.

Ternon, J. F., C. Oudot, A. Dessier, and D. Diverres, A tropical sink for atmospheric CO_2 in the Atlantic ocean: the role of the Amazon River discharge, *in press, Mar. Chem.*, 1999.

Vialard, J., and P. Delecluse, An OGCM Study for the TOGA Decade. Part II: Barrier layer formation and variability, *J. Phys. Oceanogr., 28*, 1089-1106, 1998.

Ward, M. N., and C. K. Folland, Prediction of seasonal rainfall in the north Nordeste of Brazil using eigenvectors of sea-surface temperature, *Int. J. Climatol.*, 11, 711-743, 1991.

Yoo, J. M., and J. A. Carton, Annual and interannual variations of the freshwater budget in the Tropical Atlantic Ocean and the Caribbean Sea, *J. Phys. Oceanogr.*, 20(6), 831-845, 1990.

Zebiak, S. E., Air-sea interaction in the equatorial Atlantic region, *J. Climate, 6*, 1567-1586, 1993.

B. Bourlès, and Y. Gouriou, Centre IRD de Bretagne, B.P. 70, 29280 Plouzané, France. (bourles@ird.fr; gouriou@ird.fr;)

K. Pailler, LPO, UBO, UFR Sciences, 6, avenue Le Gorgeu, B.P. 809, 29285, Brest Cedex, France (Karine.Pailler@univ-brest.fr;)

(Received December 31, 1998; revised March 30, 1999; accepted May 18, 1999.)